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(54) PLASMA ARC CUTTING PROCESS AND APPARATUS

Plasmabogen-Schneidverfahren und Vorrichtung

PROCEDE DE DECOUPE A L'ARC AU PLASMA ET DISPOSITIF

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Description

Background of the Invention

[0001] This invention relates in general to plasma arc cutting and welding processes and apparatus for dual flow piercing and cutting of metal workpieces that is faster, has a better cut quality, and protects the torch against splattered molten metal through the use of a high velocity gas secondary gas flow of well-defined flow conditions. More specifically, it relates to an apparatus and methods according to the preamble of claims 1, 15 and 19 (see WO-A-91/02619).

[0002] Plasma arc torches have a wide variety of applications such as the cutting of thick plates of steel and the cutting of comparatively thin sheets of galvanized metal commonly used in heating, ventilating and air conditioning (HVAC) systems. The basic components of a plasma arc torch include a torch body, an electrode (cathode) mounted within the body, a nozzle (anode) with a central exit orifice, a flow of an ionizable gas, electrical connections, passages for cooling and arc control fluids, and a power supply that produces a pilot arc in the gas, typically between the electrode and the nozzle, and then a plasma arc, a conductive flow of the ionized gas from the electrode to a workpiece. The gas can be non-oxidizing, e.g. nitrogen, argon/hydrogen, or argon, or oxidizing, e.g. oxygen or air.

[0003] Various plasma arc torches of this general type are described in U.S. Patent Nos. 3,641,308 to Couch and Dean, 3,833,787 to Couch, 4,203,022 to Couch and Bailey, 4,421,970 to Couch, 4,791,268 to Sanders and Couch, and 4,816,637 to Sanders and Couch, all commonly assigned with the present application. Plasma arc torches and related products are sold in a variety of models by Hypertherm, Inc. of Hanover, New Hampshire. The MAX 100 brand torch of Hypertherm is typical of the medium power torches (100 ampere output) using air as the working gas and useful for both plate fabrication and HVAC applications. The HT 400 brand torch is typical of the high power torches (260 amperes) often using oxygen as the working gas. High power torches are typically water cooled and used to pierce and cut thick metal sheets, e.g. 25.4 mm (1 inch) thick mild steel plate.

[0004] Design considerations of these torches include cooling the torch since the arc produces temperatures in excess of 10,000°C which if not controlled cold destroy the torch, particularly the nozzle. Another consideration is that the arc must be controlled, both to protect the torch itself from the arc and to enhance the quality of the cut being made in a workpiece. An early invention of one of the present applicants described in U.S. Patent No. 3,641,308 involved the use of a flow of cooling water in the nozzle of a torch to constrict the arc and thereby produce a better quality cut. It has also been found that the cut quality can be greatly enhanced if the plasma is caused to swirl, as by feeding it to the plasma chambers through a swirl ring having a set of off-center holes.

[0005] In cutting parts from sheet metal, a cut often begins by piercing the sheet at an interior point. Because the metal is not cut through when the piercing begins, the molten metal cannot run out of the kerf under the force of gravity. It is therefore splashed upwardly onto the torch. This is undesirable because the metal can destabilize the arc, causing it to gouge the nozzle, and it can adhere to the nozzle, which will often lead to double arcing, where the plasma arc flow from the electrode to the nozzle, and then to the workpiece via a conduction path of molten metal. Both gouging and double arcing reduce the nozzle life, or destroy it. It is also important that the resulting cut be smooth, as free of dross as possible, and have a cut angle that is preferably at or near 0°, that is, with the "good" side of the kerf having a surface that is perpendicular to the metal sheet itself.

[0006] In the past, to control gouging and double arcing due to splattered metal, the solution for high current (200 amperes or more) torches has been to use a multi-piece nozzle with water injection cooling. Typical such nozzles sold by Hypertherm, Inc. are illustrated in schematic form in Figs. 1A and 1B. Hypertherm Model Nos. HT400 0.099, HT400 0.166 and PAC500 0.187 correspond to Fig. 1a and use a ceramic nozzle face cooled by water. Fig. 2B shows a variation on this design which is sold by Hypertherm, Inc. as its Model PAC500 0.250.

[0007] For low current operation, 0-200 amperes, water injection cooling is less practical due to its cost and the energy drain from the plasma by the water cooling. The common commercial solution for low power, air cooled torches was simply to allow the metal to attach the torch parts and then replace them. A typical nozzle life such for such a torch operating at 40-50 amperes when piercing and cutting 6.35 mm (1/4 inch) mild steel is about one hour. There is clearly a cost associated with the replacement parts, the productive time lost during the replacement process, as well as safety considerations that arise whenever a torch is disassembled and reassembled.

[0008] Gas cooling of nozzles is also known. It usually involves a dual flow, that is a primary flow of a plasma gas and a secondary flow. They can originate at a common inlet, or separate inlets. The primary flow must be formed by an ionizable gas; the secondary flow is not necessarily ionizable. The primary flow passes through the plasma chamber where it is ionized and exits the torch through its nozzle to form a plasma jet. The secondary gas flows outside the nozzle to form a cold layer of non-ionized gas around the arc. In conventional torches the temperature and velocity of the primary or plasma gas are much higher than those of the secondary gas flow.

[0009] While the cutting capabilities of the torch are principally a function of the plasma jet, the secondary flow can be important to cool the torch and to create a

protected gaseous environment at the workpiece. Fig. 2A shows a typical use of a secondary flow of gas over the outer surface of a nozzle toward the workpiece. This arrangement is used for low current applications; nozzles of this type are sold by Hypertherm, Inc. as its model Nos. HT40 0.038 and MAX100 0.059. Fig. 2B show another gas cooling arrangement with a ceramic insulating sleeve at the lower end of the nozzle to protect the nozzle against contract against the workpiece. The ceramic, however, is brittle and this arrangement offers no protection of the nozzle during piercing.

[0010] U.S. Patent No. 4,389,559 to Rotolico et al. and U.S. Patent No. 4,029,930 to Sagara et al. are examples of plasma torches for underwater spraying and welding applications, respectively where a sheath of secondary gas shields the zone where the arc is acting against the surrounding atmosphere, whether air or water. U.S. Patent No. 4,816,637 to Sanders and Couch discloses a high current underwater cutting torch with an inwardly directed radial flow of air at 0 to 4.719 ℓ/s (10 scfm) in combination with an annular water sheath to create a water-free cutting zone and to sweep away hydrogen gas that would otherwise accumulate under the workpiece.

[0011] As noted above, the ability of a plasma torch to pierce is very important in a plasma cutting process. The commonly assigned U.S. Patent No. 4,861,962 to Sanders and Couch discloses the use of a metallic, electrically floating shield that substantially surrounds the nozzle to block metal splattered on piercing. A secondary gas flow between the shield and the nozzle cools these components. Canted ports upstream introduces a swirl into the secondary flow to help stabilize the arc and improve the cut quality. Bleed ports in the shield also draw off a portion of the cooling flow to allow an increased overall flow for better cooling without destabilizing the arc during cutting. This solution is, however not adequate for high-definition (sometimes termed high-density) torches which have a concentrated arc and require more cooling than a gas can provide. The secondary flow is relatively low in order to maintain the cut quality. The gas functions to cool the torch and to assist in stabilizing the arc.

[0012] In dual flow torches, when the primary gas is oxygen or air, the secondary gas is usually air. When the primary gas is nitrogen, the secondary gas is usually carbon dioxide or nitrogen. These combinations produce a suitable plasma jet without an unacceptable level of interference by the secondary gas with the cut. With these secondary gases, the kerf usually exhibits a positive cut angle of 1 to 2 degrees and top and bottom dross. Cut speed and quality are otherwise about the same as if no shield was used.

[0013] It is also known to provide different gases, or mixes of gases, for different phases of the cutting operation. For example, Japanese Published Document No. 57-68270 of Hitachi Seisakusho K.K. discloses a preflow of argon during a pilot arc phase, and a switch to hydrogen gas for the cutting, followed by a return to argon after the cutting is terminated. Japanese Published Application No. 61-92782 of Koike Oxygen Industry, Inc. which discloses a nitrogen-oxygen mix as a preflow plasma gas on start up, followed by an oxygen plasma flow. Both of these flows are for the plasma gas, not a secondary gas. This publication teaches that a plasma or primary gas preflow of about 85% nitrogen, 15% oxygen is best to extend electrode life. U.S. Patent No. 5,017,752 to Severance et al. discloses a flow of a non-oxidizing gas during pilot arc operation which is switched to a pure oxygen flow when the arc transfers. These flows are, again, of primary gas only. Various patents and publications also disclose patterns of gas flow and timing considerations. U.S. Patent No. 4,195,216 to Beauchamp et al., for example, discloses various modes of operating a plasma-wire welder in a manner that fills the keyhole at the end of the weld by adjusting the wire feed rate in coordination with changes in the gas flow and the arc current.

[0014] WO-A-91/02619 discloses a dual flow torch with a flow control system for the selection of flow rates for the secondary gas depending on the cutting conditions.

[0015] Applicants are not aware of a torch where an extremely high velocity flow of a secondary gas is used as a gas shield to protect the nozzle and other torch components adjacent the workpiece against splattered molten metal on piercing. Heretofore the lack of uniformity of the flow and flow hysteresis have made the direct interaction of a high velocity gas flow with the plasma jet a situation to be avoided. Applicants are also not aware of the use of a mixture of gases as a secondary gas flow in order to speed the cut and/or increase the cut quality adjustably through a change in the mix of gases forming the secondary gas. In particular applicants are not aware of any secondary gas flow using a mixture of nitrogen and oxygen where the ratio of gases in the mixture is opposite to that of air. Applicants are also not aware of a high definition plasma arc torch that uses a gas shield, this mixture of secondary gases, or flow controls that allow sudden, precise and large changes in the gas flow rates through the torch.

[0016] It is therefore a principal object of this invention to provide a plasma arc torch and method of operation that protects the torch against gouging and double arcing during piercing.

[0017] Another object of this invention is to provide a plasma arc torch and method of operation which increases cutting speed and produces a kerf of enhanced cut quality.

[0018] A further object of this invention is to provide the foregoing advantages for a high-definition torch.

[0019] Another object is to provide the foregoing advantages, including a cut that has a smooth side surface, a good cut angle, and is substantially free of top dross.

[0020] Still another object is to provide the foregoing

advantages and also the ability to adjust the cutting operation to adapt to different materials and cutting requirements depending on the application without any changes in equipment.

Summary of the Invention

[0021] To solve the above mentioned principal object, there is proposed a torch according to claim 1 and a method according to claim 15 or 19.

[0022] A plasma arc cutting system according to this invention has a dual gas flow, with a secondary flow at an extremely high rate, 3,4 m^3/h (e.g. 120 scfh), during a piercing of a sheet metal workpiece, as compared to a typical operating flow rate of 0,57 m^3/h (20 scfh). The high velocity secondary flow is directed radially inwardly onto the arc. This flow is characterized by an extreme uniformity in time and space, may have a swirling flow pattern, and is close positioned to an annular exit orifice with respect to the transferred arc. The secondary flow is preferably a mixture of oxygen and nitrogen. At least 40% of the flow is oxygen, and the flow rates are in a range of flow rate ratios of about 2:3 to about 9:1. Preferably the flow rate ratio is about 2:1. The plasma gas flow for a high definition torch with a rating of 15 amperes is typically 700 scfh. The present invention also includes primary and secondary gas flow controls that allow a quick charging and discharging of the flow lines in order to accommodate sudden large changes in flow rates without loss of control over the arc.

[0023] The plasma arc torch has a secondary gas cap mounted on its lower end with a front face interposed between a nozzle mounted on the torch and the workpiece. A water-cooled cap is mounted between the nozzle and the secondary gas cap to define a water cooled chamber adjacent the outer surface of the nozzle for high efficiency cooling. A swirl ring may be mounted between the water cooled cap and the secondary gas cap immediately upstream of the annular exit orifice. It contains a set of canted holes that introduce a swirl in the gas passing through it. A prechamber is upstream of the swirl ring, fed by a flow restricting orifice to create a pressure drop in the secondary gas feed line across the water-cooled cap. This pressure drop, prechamber and downstream swirl ring produce the flow characteristics of the present invention.

[0024] The nozzle is characterized by a large head that surrounds an exit port for the plasma jet and a sharp cut back or recess to a conical body portion. This nozzle design promotes cooling of the nozzle and allows a reliable metal-to-metal seal of the nozzle to a water-cooled cap, or equivalent component. Preferably, the secondary gas cap has a first, generally cylindrical portion that mounts on an insulating member, a transition portion that inclines toward the plasma jet, and a replaceable face portion that extends over the lower end of the torch, opposite the workpiece, with a central port aligned with the exit port of the nozzle and closely surrounding it. Preferably the face portion has a set of bleed/vent ports angled away from the jet, a locating and mounting recess at its outer edge, a groove to hold an o-ring seal, and a locating groove for the swirl ring.

[0025] Preferably, the flow controls of the present invention include a microprocessor controlled network (or "circuit") of conduits, valves, meters, and vents that provide a primary gas and a mixed secondary gas in variable ratios of two gases at multiple preselected flow rates, e.g. a preflow and an operating flow. In a preferred form oxygen and nitrogen supply lines each feed a flow meter that makes the flow rate independent of the upstream pressure. The oxygen supply flows to the plasma gas line and to a secondary gas circuit. These two oxygen flow lines and one nitrogen flow line in the secondary circuit each has a solenoid actuated flow meter bypass valve, followed by three parallel branches that each have another solenoid actuated valve and a needle valve. One branch establishes a preflow. A second branch establishes an operating flow. The third branch allows a sudden increased flow of gas to provide a "quick charge". This quick charge is due to a flow path that bypasses the flow restricting valves in the other branches.

[0026] The output of the oxygen and nitrogen secondary gas lines are combined into a single secondary feed conduit leading to the secondary gas inlet at the torch. This feed conduit and the primary and secondary gas feed lines adjacent the torch are vented to atmosphere through a solenoid actuated three way valve. Opening of the two vents in the secondary gas line briefly during the transfer from a pilot arc mode to a transferred arc mode allows the secondary gas flow to drop quickly to its operating value for cutting. Opening all three vents on plasma cut off provides a quick discharge of the gas flows to the torch. In order to have a strong secondary gas flow throughout piercing, there is a time delay between the transfer of this plasma to the workpiece and the switching from the preflow to the operating flow of the secondary gas.

[0027] These and other features and objects of the present invention will be more fully understood from the following detailed description which should be read in light of the accompanying drawings.

Brief Description of the Drawings

[0028]

- Fig. 1A is a simplified view in vertical cross section of a prior art electrode and multi-piece nozzle of a high-current, water-injection plasma arc torch;
- Fig. 1B is a view corresponding to Fig. 1A of an alternative prior art multi-piece, water injection nozzle;
- Fig. 2A is a simplified view in vertical cross section of a prior art one-piece nozzle of a plasma arc torch for use with low currents;

Fig. 2B is a view corresponding to Fig. 2A of an alternative prior art one-piece nozzle embodiment for low current use using a cylindrical ceramic shield;

Fig. 3A is a view in vertical section of a high definition water and air cooled plasma arc torch according to the present invention which shows the plasma gas and secondary gas passages;

Fig. 3B is a view in vertical section of the present invention showing the water cooling passages;

Fig. 3C is a detailed view in vertical section of the nozzle and exit port area of the torch shown in Fig. 3A;

Fig. 3D is a view in horizontal section of the swirl ring shown in Fig. 3A;

Fig. 4 is a schematic flow control circuit according to the present invention providing a mixed gas secondary gas flow at varying flow rates and with a quick charge and quick discharge capability; and

Fig. 5 is a timing diagram for the control circuit shown in Fig. 4.

Detailed Description of the Preferred Embodiments

[0029] Figs. 3A and 3B show a plasma arc torch 10 according to the present invention. It has a multi-component body 12 including a generally cylindrical main body portion 12a formed of an insulating material such as FR4 fiber glass or Delrin. Anode block 14 secured in the body portion 12a has an opening 14a that receives a plasma gas conduit 16 and an opening 14b that receives secondary gas conduit 18, both the plasma gas conduit 16 and the secondary gas conduit 18 pass through an insulator block 20. A nozzle 28 is mounted immediately below an electrode 24 in a spaced relationship to define a plasma arc chamber 30 therebetween where plasma gas fed from a swirl ring 32 is ionized to form either a pilot arc between the electrode and the nozzle or a transferred arc, or plasma jet, 34 between the electrode and a workpiece 36. The jet 34 pierces the workpiece and then cuts a kerf 38. Note that swirl 32 is comprised of two pieces 32a and 32b. Radial ports 32c on swirl ring port 32a distribute the plasma gas flow evenly to injection ports 32d on swirl ring port 32b. The electrode 24 has a hafnium insert 24a.

[0030] As shown, the nozzle has a configuration specially adapted for a high definition torch with a narrow exit port 28a, a large diameter nozzle head 28b to act as a good heat sink, a severe cutback or recess 28c, and a conical body portion 28d. This design provides good heat transfer and therefore cooling of the nozzle by water circulated over the outside of the nozzle. It also facilitates a reliable metal-to-metal seal at 66a between the nozzle head and a like inclined end surface of a water-cooled cap 66. The various component parts are assembled with fluid tight seals provided by sets of o-rings each seated in an associated annular groove, and the metal seal 66a.

[0031] A gas source 42 provides a flow of a plasma gas through a primary gas control circuit 44a (Fig. 4) to a plasma gas inlet 10a of the torch 10. A source 46 of a second gas flows through a flow control circuit 44b to a secondary gas inlet 10b of the torch. The secondary gas in the preferred form shown includes a mix of gases from both sources, as is discussed in more detail below. In the torch the plasma gas follows a flow path 48 that includes tube passage 16a, vertical passage 48a, radial port 48b to the swirl ring 32 and then to the plasma chamber 30 where it is ionized. The secondary gas follows a flow path 50 that includes tube passage 18a, a vertical passage 52, a radial port 54, a flow restricting orifice 56, a prechamber 58, a secondary gas swirl ring 60 and an annular exit orifice 62.

[0032] This secondary flow path, and in particular orifice 56, prechamber 58 and the swirl ring 60 is a principal feature of this invention. It introduces a high degree of flow uniformity and control over the flow at a point immediately adjacent to the transferred plasma arc 34. The swirl ring 60 contains a set of off-center, or canted holes 64 which introduce a swirling movement to the flow which facilitates the interaction of the secondary gas stream with the jet 34 and has a beneficial effect on the cut quality. The swirl ring is formed of an insulating material such as a high temperature plastic, preferably the product sold by I.E. du Pont de Nemours under the trade designation Vespel. As shown, the exit orifice 62 has a flat annular portion 62a, a conical portion 62b directed downwardly and radially inward, and a final flat annular portion 62c that is generally parallel to the workpiece 36. The orifice passages 62b and 62c mirror the outer dimensions of the adjacent nozzle surfaces.

[0033] The prechamber 58 acts as a local gas supply to the swirl ring 60. The flow restricting orifice 56 creates a pressure drop at the opposite end of the prechamber 58 from the swirl ring. The orifice 56 and prechamber 58 isolate the swirl ring from upstream pressure and flow rate fluctuations. To draw an electrical analogy, the orifice 56 and prechamber 58 act as a smoothing capacitor in an a.c. circuit. On shut off, when the arc current is cut off, the gas in the plasma chamber cools rapidly, leading to a sudden outrush of gas. Gas in the secondary flow path, absent this invention, would be drawn out in this outrush by the Venturi effect. However, the orifice 56 choke off the outrush so that only the comparatively small supply of gas in the prechamber 58 is drawn out. This supply is calculated to continue the arc stabilization of the secondary gas during cut off, but to have the secondary gas flow cease generally coincident with the extinction of the arc. This arrangement provides a secondary flow from the exit orifice 62 which is high uniform, both in time and spatially.

[0034] In the high definition torch of Fig. 3A - 3D, the arc is highly constricted as compared to conventional plasma arcs. It also has a high energy density. In a standard plasma cutting torch the current density is approximately 3.88×10^7 A/m^2 (25,000 Amp/ sq. inch);

in a high density plasma the current densities can be as high as 1.24 x 10^8 A/m^2 (80,000 Amp/ sq. inch), measured in the nozzle base. A 15 ampere current is typical. Water cooling has been found to be necessary. To this end, the water-cooled cap 66 is threaded into the lower end of the anode block 14, with an o-ring seal at 68 and the face-abutting metal-to-metal seal 66a to the upper edge of the nozzle head 28b. Water flow 45a is passed through a water chamber 70 defined by the cap 66, the outer surface of the nozzle 28 and the lower end of the anode block 14. The cooling water 45 flows into the torch through passages 47 which includes water inlet tube 17 which is fitted into opening 15a in the cathode block 15. Water flows from the tube outlet 47a through annulus 47b, radial holes 47c in both the cathode block 15 and insulator 13, annulus 47d, radial holes 47e, annulus 47f to the drill holes 47g. Here the flow splits into two flows 45a to the nozzle and 45b to the secondary cap via vertical passage 47h and annulus 47i respectively. Flow 45a returns from chamber 70 via vertical passage 47j which joins returning flow 45b at hole 47k then flows out of the torch through tube conduit 19 which is fitted to nozzle block 14 at opening 14c.

[0035] Another principal feature of this invention is a secondary gas cap 72 threaded at 74 to the insulating body and gas sealed by o-rings 40c and 40d to the body. The secondary gas cap has a first portion including a cylindrical body 72a terminating in conical wall portion 72b with a step 72c in its side wall. A second or face portion 72d includes a step 72e that mates with step 72c, a groove 72f that holds o-ring 40e, vent ports 72g, a recess 72h that holds and positions the swirl ring 60 at its lower edge, an exit orifice 72i centered on the nozzle exit orifice and closely spaced around the plasma jet, and wall portions 72j, 72k and 72l that mirror the nozzle in a parallel spaced relationship and define together with the nozzle the exit orifice 72i.

[0036] The cap 72 is in a parallel spaced relationship with the cap 66 with the gap between them defining the prechamber 58. The secondary gas cap not only defines the secondary flow path, it also acts during piercing as a mechanical shield against splattered metal. The lower portion of the cap, particularly the face piece 72d, intercepts any molten metal sprayed upwardly that is not swept away by the gas shield of the present invention, that is, a strong shielding flow of secondary gas this impinges on the plasma jet and is turned to flow radially outwardly between the cap 72 and the workpiece. Note that the central exit orifice 72i has a very small diameter to closely surround the plasma jet 34 with as small a clearance as is possible without risking gouging. The shield is also electrically floating. It is mounted on an insulating material, the body part 12a, and is spaced from adjacent metallic members such as the nozzle 28 and water cooled cap 66, and the swirl ring 60 is formed of an insulating material. As a result, should any molten metal adhere to it, it will not be part of a conductive path for a double arcing. The vents 72g encircle the exit orifice 72i. They are sized and numbered so that during the cutting operation of the torch, they divert or bleed off a sufficient portion of the secondary flow to atmosphere that the flow reaching the plasma jet does not adversely impact on its operation. To this end, the ports are preferably canted away from the plasma jet at a small acute angle, as shown. On the other hand, on start up and during piercing, very high flow rate causes the secondary gas flow to blow by the vents 72g with little diversion of the flow to atmosphere through them. On shut down, as the secondary gas pressure in the path 50 and prechamber 58 drops, the vents 72g provide a vent path to atmosphere to assist in rapidly decreasing the secondary gas pressure. Note that because the face piece 72d is a separate component of the torch, if it becomes worn or damaged it can be replaced without replacing the entire cap 72.

[0037] By way of illustration, but not of limitation, a torch 10 having a rating of 15 amperes has an overall diameter of about 38.1 mm (1.5 inches), exit orifice 72i, has a diameter of about 1.52 mm (.060 inch), a swirl ring 60 has an inside diameter of 7.62 mm (.300 inch) and outside diameter of 10.16 mm (.400 inch) and 6 equiangularly spaced, off-center holes 64 with a diameter of 0.41 mm (.016 inch). The flow restriction orifice 56 has a diameter of 0.76 mm (.030 inch) and the prechamber 58 has an internal volume of approximately 3.23 cm^2 (.500 sq. inches). The exit orifice has a radial flow path from the swirl ring 60 to the outer diameter of the exit orifice 72i of about 0.20 mm (.008 inch). The vents 72g are twelve in number and have a diameter of 4.06 mm (0.16 inch).

[0038] Another principal feature of this invention is the use of a secondary gas that is a mixture of a non-oxidizing gas -- such as nitrogen, argon, helium, or any of the inert gases -- and an oxidizing gas such as oxygen or air, where the oxidizing gas comprises at least 40% of the mixture, measured by flow rates. In the preferred form, with oxygen as the plasma gas, the secondary gas is formed of a mixture of oxygen and nitrogen (argon) with their respective flow rates in a ratio in the range of about 2:3 to about 9:1, and preferably about 2:1. The 2:1 preferred ratio is almost exactly opposite to the ratio of these gases forming air. The gases are commercially pure and are substantially free of water and oil. When these gases are used in this ratio as a shield gas as described above with respect to Figs. 3A, 3B, 3C and 3D, the cutting speed of the torch in mild steel has been found to increase dramatically. In addition, the cut angle changes from 1° to 2° positive with an air shield to about 0°, or generally perpendicular to the workpiece. Further the top dross can be controlled to a point where it is negligible.

[0039] The exact flow ratio for the oxygen and nitrogen flows forming the secondary gas can be determined empirically by cutting with the torch and adjusting the flows until the cut angle or other cut parameter or

parameters are optimized. In making these adjustments it has been found that an increase in the oxygen flow will increase the cutting speed (up to about three times the speed of a conventional cutting speed with no gas shield). It also causes the cut angle to become very negative , up to 4° to 5° for a pure oxygen flow. Also, the cutting surface becomes increasingly rough and it exhibits a zig-zag pattern. The reason for these effects is not well understood, but it is believed that a rich oxygen environment surrounding the plasma jet assists a chemical reaction between the metal and the oxygen which releases thermal energy that assists in melting the metal. The cut angle may also be explained as an effect of the oxygen secondary flow on the shape of the plasma jet 34.

[0040] Increasing the nitrogen flow, on the other hand, appears to influence cutting speed only to the extent such an increase is at the expense of the oxygen flow rate. A pure nitrogen flow is characterized by a cutting angle that is 2° to 3° positive, a smooth cut surface, and some increase in dross as compared to cutting with no shield gas. It has been found that by changing the oxygen-nitrogen mixing ratio and the total secondary gas flow one can adjust the cutting angle from about positive three degrees to negative three degrees. An increase in the oxygen in the mix and an increase in the total flow makes the cut angle more negative. Thus, the cutting angle can be tuned to a desired value simply by changing the secondary gas mixture, rather than by changing the geometry of the torch, as was the case in the past. Also, when the cut angle is maintained at a zero or negative value, top dross is substantially eliminated.

[0041] The oxygen rich secondary gas mixture of the present invention also improves the piercing capabilities of the torch 10. A pierced hole made with an oxygen rich secondary gas according to the present invention is cleaner and can penetrate greater thicknesses of sheet metal than identical torches operating with different mixtures such as air.

[0042] Fig. 4 shows the gas flow control circuit 44 which controls the flow of plasma and secondary gases from sources 42 and 46 to the inlets 10a and 10b of the torch 10. The plasma gas, which for the purposes of this discussion will be taken as oxygen, flows from the source 42 through a nitrogen/oxygen solenoid selector valve SV15 (normally in the oxygen select position). It is then split into a plasma gas flow along line 76 and a secondary gas (oxygen portion) flow along line 78 to the oxygen feed line 86 in the secondary gas section 44b of the control 44. The secondary gas supply 46 feeds a conduit 82 which has a branch line 84 to the switch SV15 in the event that nitrogen is desired as the plasma gas. Pressure switches PS1 and PS2 in lines 76 and 82 do not allow the plasma cutting system to work if the pressure falls below a preset value.

[0043] In the preferred form shown, using oxygen as the plasma gas and a mixture of oxygen and nitrogen as the secondary gas, three feed lines 76, 78 and 82 are used. Each has a flow meter FM1, FM2, and FM3, respectively, and a pressure gauge PG1, PG2, PG3 connected in series with the flow meter. The flow meters ensure precise settings of the flow rates of both plasma and shield gas flows. Three bypass solenoid valves SV8, SV9 and SV10 are connected in parallel with the three flow meters, respectively. These valves are three way valves that are normally open to the bypass line. This serves to protect the flow meters during transient times and during steady state three valves are closed allowing the flow measurement.

[0044] Three normally closed solenoid valves are connected in parallel with each other at the downstream side of the flow meter for each line 76, 78 and 82. Each solenoid valve is followed by a needle valve. Each set of these solenoid valves has one that controls the preflow, one valve that controls the operating flow, and a third valve that provides for a quick charge. For oxygen plasma line 76, the preflow valve is SV2, the operating valve is SV1 and the quick charge valve is SV3. The associated needle valves are MV2, MV1 and MV3, respectively. For the oxygen secondary gas line, these three solenoid valves are SV5, SV4 and SV16, followed by needle valves MV5, MV4, and MV8, respectively. For the nitrogen secondary gas line, these solenoid valves are SV7, SV6, and SV17, followed by associated needle valves MV7, MV6, and MV9 respectively. The outputs from the valves SV4, SV5, SV6, SV7, SV16, and SV17 are combined to single secondary gas lead 86 connected to the secondary gas inlet 10b at the torch. The output of the oxygen and nitrogen secondary gas lines is therefore combined into a single flow to the torch.

[0045] The gas control circuit 44 also include four three way vent valves that are each normally open to atmosphere. They are also electrically actuated solenoid valves. Venting valve SV11 is connected to the oxygen plasma gas line at a gas console 88 that houses the gas control circuit 44. A like venting valve SV13 is also connected in line 80, but at the torch. This valve has a flow restricting orifice CO1 in the vent passage leading to atmosphere. It controls the decay of the plasma gas pressure in the nozzle on shut down. It is adjusted so that the gas pressure maintains the arc while the current is on, but rapidly dissipates the plasma gas pressure when the current is cut off. In the secondary gas feed line 86, a vent valve SV12 is connected to the line at the console 88 and a like valve SV14 is connected in the line at the torch. The gas circuit 44 also has pressure gauges PG4 and PG5 connected at the console 88 to the combined outputs from the preflow, operating flow and quick discharge valves. PG4 reads the oxygen plasma pressure on line 80, PG5 reads the secondary gas pressure on line 86.

[0046] During piercing the preflow valves are energized to open, with the operating valves and quick charge valve closed during most of the preflow. In this situation, the needle valves MV5 and MV7 control the mix ratio of the oxygen and nitrogen flows forming the

secondary gas. As discussed above, this ratio is preferably set at about 2:1, but adjustments can be made to optimized the flow for the given operating conditions and to optimize varying cut parameters. Also, the preflow through the valves SV5, MV5, SV7 and MV7 is set at a flow rate many times greater than the operating flow rate set by valves SV4, MV4, SV6, MV6. A typical value for the total secondary gas preflow is 3,4 m^3/h (120 scfh), and 0,57 m^3/h (20 scfh) for the operating flow. Suitable three way solenoid valves are manufactured by Automatic Switch Company under Model No. AFP33183 or by MAC Valves Inc. under Model No. 111B - 111BAAA. The valves are all controlled by a central microprocessor 90 that is programmed to operate the gas control circuit 44 in the manner illustrated by the timing diagram of Fig. 5.

[0047] Fig. 5 it illustrates the operating state of all of the valves in the circuit 44 during a full cycle of operation of the torch 10, from t_0 when a start signal is given to the system by an operator to a complete shut off of the arc current and gas flows at the end of t_6. Fig. 5 also shows the corresponding arc current, voltage, and gas pressures at the nozzle (in the plasma arc chamber) and the secondary shield gas pressure measured at the prechamber 58 between caps 66 and 72.

[0048] As soon as the start command is issued, the three preflow solenoid valves SV2, SV5 and SV7 are energized to open. The four venting valves SV11, SV12, SV13 and SV14 are energized to closed position (they are normally open). The three quick charge valves SV3, SV16 and SV17 are also energized at the same time. The quick charge valves bring the nozzle and shield gas pressures up to their full preflow values in time t_1 for the plasma gas and in time t_2 for the shield gas. The quick charge valves work to quickly charge lines 80 and 86 because they allow the flows to bypass the flow restriction in the preflow and operating flow branches. They allow a sudden, step function increase in the flow. The preflow continues for a total elapsed time of 1 to 2 seconds, long enough to stabilize the preflows. As shown in Fig. 5, high voltage spikes 91 are applied at a high frequency to the torch after about 1 second of preflow to initiate a pilot arc, shown at 92. Once breakdown occurs for the pilot arc, the voltage falls.

[0049] At the transfer of the arc to the workpiece, the current is ramped up as shown at 94, to its operating level 96 at the completion of the transfer. The voltage drops on transfer and the gas pressure rises as the plasma gas in the torch at the nozzle is heated to extremely high temperatures and the gas flow is choked at the nozzle orifice 28a. During the transfer, piercing occurs. To provide the high velocity gas shield of the present invention, the large secondary gas preflow is maintained for about 60 ms after the beginning of the transfer. This high flow rate secondary gas preflow blows away molten metal splashed upwardly toward the torch before it can reach the torch itself. The flow surrounds the plasma jet and is radially inwardly directed. It interacts with the jet, but most of the flow turns and flows radially away from the jet sweeping outwardly and downwardly in the region between the workpiece and the lower end of the torch. It creates a moving, cool gas boundary between the cap 72 and the workpiece. This strong flow exists during piercing, but is greatly reduced during normal cutting. During cutting the mechanical shielding of the cap 72 protects the nozzle against double arcing.

[0050] After about 50 ms from the beginning of the transfer the plasma gas quick charge valve SV3 is reopened for a time t_2 to bring the plasma gas flow up to its full operating valve quickly. Also after 50 ms from the beginning of the transfer operating flow valves for both the plasma and shield gas open SV1, SV4, SV6. After a time t_3 from transfer, the two shield line vent valves SV12 and SV14 are opened briefly, for time t_4 as shown, to assist the pressure in the secondary line in falling to a level consistent with a much lower operating flow. This is the secondary gas quick discharge. The valves remain in these operating positions during operation except that the three flow meter bypass valves are energized about 300ms after the commencement of transfer. This is after the flows reach their steady state values. To stop operation of the torch, a STOP command (i) deenergizes and closes the three operating valves SV1, SV4 and SV6, (ii) deenergizes the four vent valves to open them to atmosphere and thereby facilitate a quick discharge of the plasma and secondary gases, and (iii) deenergizes the flow meter bypass valves. From the STOP command to the end of t_6 the arc current is ramped down. At the end of t_6 it is cut off completely. There is a small residual pressure at the nozzle, but it rapidly dissipates so that there is substantially no strong swirling gas flow in the plasma chamber at current off, end of t_6. This condition has been found to be highly conducive to reducing electrode wear.

[0051] There has been described an apparatus and process for a plasma arc torch that protects the torch against double arcing on piercing and during cutting of sheet metal. There has also been described a gas shield for this protection using a very high flow of a secondary gas during the preflow only. The invention also describes an oxygen-rich secondary gas flow for the preflow on piercing and the operation flow that produces a significantly faster and higher quality cut than heretofore attainable using shielded torches or high definition torches. There has also been described a system for precisely controlling the gas flows to the torch, both primary and secondary, both preflow and operating flow, so that a high flow rate secondary gas can provide a gas shield, but the operating flow is low enough that it does not detract from the cut quality. This control is sufficiently rapid that the plasma arc is maintained well under control despite large and sudden charges in the gas flows through the torch. There has also been described a nozzle which particularly adapted to the high temperature, water-cooled operating environment

of a high definition torch.

[0052] While this invention has been described with respect to its preferred embodiments, it will be understood that various modifications and variations will occur to those skilled in the art from the foregoing detailed description and the accompanying drawings. For example, while the invention has been described with respect to a high definition torch with two different gases, one oxidizing and the other non-oxidizing, the invention can be used in conventional torches and with a single type of gas. Use of a single gas, however, provides only the gas shield advantages, not the increased cutting speed, cut quality, or tunability inherent in the oxygen-rich gas composition preferred for use as the secondary gas for applications where an active gas such as oxygen is optimal for use as the plasma gas. Also, while a network of valves and vents actuated electronically under the control of a microprocessor has been described, other arrangements can be used to supply the plasma and secondary gases in the right mix, at the proper times, and with a high degree of precision in the timing. For example, rather than opening an extra line using a valve to quick charge, an independent source of high pressure gas can be suddenly and briefly opened to the main feed line to provide a step function increase in the flow rate. Also, while a flow restriction orifice and prechamber are used to create a pressure drop and enhance flow uniformity, other arrangements are possible. Further, while the invention has been described with respect to a swirl ring in the secondary gas flow path, a non-swirling secondary gas flow can also be used, although with some loss of performance. These and other modifications and variations are intended to fall within the scope of the appended claims.

Claims

1. A plasma arc cutting torch (10) used in piercing and cutting a sheet metal workpiece (36) where the torch has a body (12), an electrode (24) and a nozzle (28) mounted at a first end of the body in a mutually spaced relationship that defines a plasma chamber (30), a plasma gas flow path (48) in said body that conducts a plasma gas from a plasma gas inlet (10a) to the plasma chamber (30), a secondary gas flow path (50) in said body (12) from a secondary gas inlet (10b) to an exit orifice (62) surrounding said plasma arc, the torch (12) operating in a pilot arc mode and a transferred arc mode that can commence by piercing the workpiece,

    means for producing a flow rate of said secondary gas during said piercing that is higher in comparison with the flow rate during cutting in the transferred arc mode,
    a secondary gas cap (72) mounted on said body in a spaced relationship with said nozzle (28) to define therebetween a portion of said secondary gas flow path which includes said secondary gas flow exit orifice (62);
    said secondary gas flow exit orifice (62) being adjacent the nozzle exit orifice (28a) such that said secondary gas flow is directed onto the transferred plasma arc as it leaves said nozzle exit orifice without being substantially ionised;
    said high velocity secondary gas flow rate at said exit orifice (62) is (i) highly uniform and (ii) positioned closely to the transferred plasma arc,
    characterised in that
    a water-cooled cap (66) is mounted on said body and substantially encloses the outer surface of the nozzle (28);
    said means for producing a flow rate of said secondary gas produces a flow rate during said piercing that is very high in comparison with the flow rate during cutting in the transferred arc mode such that
    said high velocity secondary gas flow has sufficient velocity at the exterior of said torch between said nozzle (28) and said workpiece (36) to blow away molten metal that flies up from the workpiece (36) to the torch (12) that may produce double arcing or gouging.

2. The plasma arc torch (10) of claim 1 wherein said means for producing a very high secondary gas flow rate includes a prechamber (58) in said secondary gas flow path (50) immediately upstream of said exit orifice (62) and at least one means for producing a pressure drop in said secondary flow path (50) between a point upstream of said prechamber (58) and the prechamber (58) itself.

3. The plasma arc torch (10) of claim 1 or 2 wherein said means for producing a high, uniform secondary gas flow rate includes a swirl ring (60) located in said secondary gas flow path (50) immediately before said exit orifice (62).

4. The plasma arc torch of claim 2 or 3 wherein said means for producing a pressure drop includes at least one flow restricting orifice (56).

5. The plasma arc torch (10) of claim 3 or 4 wherein said torch (10) is a high definition torch and wherein said means for producing a high secondary gas flow rate (50) includes (i) a water-cooled cap (66) mounted on said body (12) and substantially enclosing the outer surface of the nozzle (28) in a spaced relationship to define a water chamber (70) for cooling the nozzle (28) and (ii) a secondary gas cap (72) mounted on said body (12) in a spaced relationship with said water-cooled cap (66) to define therebetween said prechamber (58), said swirl ring (60) being mounted between said water-

cooled cap (66) and said secondary gas cap (72) adjacent their ends proximate the nozzle (28).

6. The plasma arc torch (10) according to claim 5 wherein said flow restricting orifice (56) is formed in said water-cooled cap (66) near the upstream end of said prechamber (58).

7. The plasma arc torch (10) according to claim 5 wherein said secondary gas cap (72) is formed of a first portion (72a) that is secured to the torch body (12) and projecting toward said nozzle (28), and a second portion (72d) replaceably held between said first portion (72a) and said swirl ring (60), said second portion (72d) being sealed to said first portion (72a) in a gas-tight relationship and extending generally parallel to the workpiece (36), except for a central exit port (72i) for the transferred plasma arc.

8. The plasma arc torch (10) according to claim 7 wherein said secondary gas cap (72) is formed of a metal and further comprising means for electrically isolating said secondary gas cap (72) so that it is electrically floating to avoid double areing between it and the workpiece (36).

9. The plasma arc torch (10) according to claim 8 wherein said electrical isolating means includes an insulating member (12a) forming a portion of said body (12) to which said secondary gas cap (72) is replaceably attached.

10. The plasma arc torch (10) of any one of claims 1-9 wherein said means for producing a very high secondary gas flow rate includes control means (44) for generating a sequence of control signals and a gas delivery circuit responsive to said control means that produces secondary gas flows at said high rate at least during piercing and at said operating flow rate when piercing is complete.

11. The plasma arc torch (10) according to claim 10 wherein said gas delivery circuit includes means for quickly charging said gas flows to the torch (10) and means for quickly discharging the gas flows upon completion of said piercing and then upon completion of said cutting.

12. The plasma arc torch (10) according to claim 11 wherein said means for quickly charging includes first (76,78) and second conduit (82) means for conducting said plasma and secondary gases to said plasma gas inlet (10a) and secondary gas inlet (10b) of said torch, respectively, and electrically-actuated valve means connected in parallel with each of said first (76,78) and second (82) conduit means, each of said valve means, when opened allowing a sudden increased flow of said gases to said torch.

13. The plasma arc torch (10) according to claim 12 wherein said quick discharge means includes a set of electrically-actuated solenoid valves (SV8,9,10) in said first (76,78) and second (82) conduit means, a portion of which cease selected gas flow to said torch (10) suddenly, and a second portion of which open to vent the torch (10) and said conduit means in coordination with said closing of said first portion.

14. The plasma arc torch (10) according to claim 12 wherein said high flow rate secondary gas flow (46) is a preflow in conjunction with operation in the pilot arc mode and wherein said means for quickly discharging operates with a slight delay after said flow control means terminates said preflow in favour of an operating flow.

15. A method of protecting the nozzle (28) of a plasma arc cutting torch (10) from molten metal sprayed onto it from a metallic workpiece (36) during piercing of the workpiece by a transferred plasma arc emitted from the torch (10), the torch (10) including a body (12) with a primary gas inlet (10a) and a secondary gas inlet (10b), an electrode (24), and a nozzle (28) in a mutually spaced relationship with respect to the electrode (24) to form a plasma arc chamber (30) therebetween where the plasma gas ionizes, comprising,

directing the secondary gas through the torch (10) to an exit orifice (62) placed immediately adjacent the transferred plasma arc (34) as it leaves the nozzle (28),

increasing the flow rate of said secondary gas to a high rate during said piercing,

whereby a high degree of flow uniformity of said secondary gas is created as it exits said exit orifice (62),
characterised in that

said high rate is sufficient to blow away the sprayed molten metal.

16. The nozzle protection method of claim 20 further comprising quickly charging said secondary flow when it commences piercing and quickly discharging it when it terminates piercing.

17. The nozzle protection method of any one of claims 15 or 16 wherein said highly uniform flow creating includes introducing a pressure drop upstream of said exit orifice (62) and creating a gas plenum between the point of said pressure drop and said exit orifice (62).

18. The nozzle protection method of claim 16 wherein said charging includes decreasing the resistance to said flow and said discharging includes venting said secondary flow.

19. A method of operating a plasma arc cutting torch including operation in a pilot arc mode and then transferring to a transferred arc mode for piercing a metal workpiece and then cutting the workpiece by translating the torch where the torch has a plasma gas flow and a secondary gas flow therethrough, the plasma flow forming a pilot and transferred arc and said gas flows having a preflow associated with said piercing and an operating flow associated with said cutting comprising

directing said secondary flow onto said plasma jet,

and increasing said secondary flow rate during piercing as compared to an operating flow rate for cutting when said plasma jet is in the cutting mode, characterised in that

said increased secondary flow rate is sufficient to blow away the sprayed molten metal that flies up from the workpiece to the torch and may produce double arcing or gouging.

20. The method of claim 19 further comprising

quickly charging said secondary gas flow at its commencement to produce said high flow rate as a step function

and quickly discharging said secondary gas flow upon termination of said preflow of said secondary gas.

21. The method according to any one of claims 15-20 wherein said secondary gas is a mixture of an oxidizing gas and a non-oxidizing gas mixed in a ratio in the range of about 2:3 to about 9:1 oxidizing gas to non-oxidizing gas, measured as the flow rates of said gases.

22. The method according to claim 21 wherein said non-oxidizing gas is selected from the group consisting of nitrogen and argon and said oxidizing gas is selected from the group consisting of oxygen and air.

23. The method according to claim 21 or 22 wherein said ratio is approximately 2:1.

24. The method according to any one of claims 15-20 wherein said secondary gas is a mixture of a non-oxidizing gas and an oxidizing gas where the mixture is at least 40% oxidizing gas, as measured by flow rate.

25. The method according to claim 24 wherein said non-oxidizing gas is selected from the group consisting of nitrogen and argon and said oxidizing gas is selected from the group consisting of oxygen and air.

Patentansprüche

1. Plasmalichtbogenschneidbrenner (10), der für das Lochen und Schneiden eines Werkstückes (36) aus Blech verwendet wird, wobei der Brenner ein Gehäuse (12), eine Elektrode (24) und eine Düse (28) aufweist, die an einem ersten Ende des Gehäuses in einer gegenseitig beabstandeten Beziehung montiert ist, wodurch eine Plasmakammer (30), ein Plasmagasstromweg (48) im Gehäuse, der ein Plasmagas von einem Plasmagaseintritt (10a) zur Plasmakammer (30) führt, ein Sekundärgasstromweg (50) im Gehäuse (12) von einem Sekundärgaseintritt (10b) zu einer Austrittsöffnung (62), die den Plasmalichtbogen umgibt, begrenzt werden, wobei der Brenner (12) eine Betriebsart mit Zündlichtbogen und eine Betriebsart mit übertragenem Lichtbogen hat, die mit dem Lochen des Werkstückes begonnen werden kann;

eine Einrichtung für das Erzeugen einer Strommenge des Sekundärgases während des Lochens, die im Vergleich mit der Strommenge während des Schneidens bei der Betriebsart mit übertragenem Lichtbogen höher ist;

eine Sekundärgaskappe (72), die auf dem Gehäuse in einer beabstandeten Beziehung mit der Düse (28) montiert ist, um dazwischen einen Abschnitt des Sekundärgasstromweges zu begrenzen, der die Austrittsöffnung (62) für den Sekundärgasstrom umfaßt,

wobei die Austrittsöffnung (62) für den Sekundärgasstrom der Düsenaustrittsöffnung (28a) benachbart ist, so daß der Sekundärgasstrom auf den übertragenen Plasmalichtbogen gelenkt wird, während er die Düsenaustrittsöffnung verläßt, ohne daß er im wesentlichen ionisiert wird,

wobei die Sekundärgasstrommenge mit hoher Geschwindigkeit in der Austrittsöffnung (62) (i) sehr gleichmäßig und (ii) nahe am übertragenen Plasmalichtbogen angeordnet ist;
dadurch gekennzeichnet, daß eine wassergekühlte Kappe (66) auf dem Gehäuse montiert ist und im wesentlichen die äußere Fläche der Düse (28) einschließt;

die Einrichtung für das Erzeugen einer Strommenge des Sekundärgases eine Strommenge während des Lochens erzeugt, die im Vergleich zur Strommenge während des Schneidens bei der Betriebsart mit übertragenem Lichtbogen sehr hoch ist, so daß der Sekundärgasstrom mit hoher Geschwindigkeit an der Außenseite des Brenners zwischen der Düse (28) und dem Werkstück (36) eine ausreichende Geschwindigkeit aufweist, um das geschmolzene Metall wegzublasen, das vom Werkstück (36) zum Brenner (12) nach oben fliegt, wodurch die Ausbildung eines doppelten Lichtbogens oder das Durchtrennen hervorgerufen werden könnten.

2. Plasmalichtbogenbrenner (10) nach Anspruch 1, dadurch gekennzeichnet, daß die Einrichtung für das Erzeugen einer sehr hohen Sekundärgasstrommenge eine Vorkammer (58) im Sekundärgasstromweg (50) unmittelbar stromaufwärts von der Austrittsöffnung (62) und mindestens eine Einrichtung für das Erzeugen eines Druckabfalls im Sekundärgasstromweg (50) zwischen einer Stelle stromaufwärts von der Vorkammer (58) und der Vorkammer (58) selbst umfaßt.

3. Plasmalichtbogenbrenner (10) nach Anspruch 1 oder 2, dadurch gekennzeichnet, daß die Einrichtung für das Erzeugen einer hohen, gleichmäßigen Sekundärgasstrommenge einen Wirbelring (60) umfaßt, der sich im Sekundärgasstromweg (50) unmittelbar vor der Austrittsöffnung (62) befindet.

4. Plasmalichtbogenbrenner nach Anspruch 2 oder 3, dadurch gekennzeichnet, daß die Einrichtung für das Erzeugen eines Druckabfalls mindestens eine Strombegrenzungsöffnung (56) umfaßt.

5. Plasmalichtbogenbrenner (10) nach Anspruch 3 oder 4, dadurch gekennzeichnet, daß der Brenner (10) ein Brenner mit hoher Genauigkeit ist, und daß die Einrichtung für das Erzeugen einer hohen Sekundärgasstrommenge (50) umfaßt: (i) eine wassergekühlte Kappe (66), die am Gehäuse (12) montiert ist und im wesentlichen die äußere Fläche der Düse (28) in einer beabstandeten Beziehung einschließt, um eine Wasserkammer (70) für das Kühlen der Düse (28) zu begrenzen; und (ii) eine Sekundärgaskappe (72), die am Gehäuse (12) in einer beabstandeten Beziehung mit der wassergekühlten Kappe (66) montiert ist, um dazwischen die Vorkammer (58) zu begrenzen, wobei der Wirbelring (60) zwischen der wassergekühlten Kappe (66) und der Sekundärgaskappe (72) angrenzend an deren Enden in unmittelbarer Nähe der Düse (28) montiert ist.

6. Plasmalichtbogenbrenner (10) nach Anspruch 5, dadurch gekennzeichnet, daß die Strombegrenzungsöffnung (56) in der wassergekühlten Kappe (66) in der Nähe des stromaufwärts gelegenen Endes der Vorkammer (58) gebildet wird.

7. Plasmalichtbogenbrenner (10) nach Anspruch 5, dadurch gekennzeichnet, daß die Sekundärgaskappe (72) aus einem ersten Abschnitt (72a), der am Brennergehäuse (12) gesichert ist und in Richtung der Düse (28) vorsteht, und einem zweiten Abschnitt (72d) gebildet wird, der auswechelbar zwischen dem ersten Abschnitt (72a) und dem Wirbelring (60) gehalten wird, wobei der zweite Abschnitt (72d) am ersten Abschnitt (72a) in einer gasdichten Beziehung abgedichtet wird und sich im allgemeinen parallel zum Werkstück (36) erstreckt, mit Ausnahme einer mittleren Austrittsöffnung (72i) für den übertragenen Plasmalichtbogen.

8. Plasmalichtbogenbrenner (10) nach Anspruch 7, dadurch gekennzeichnet, daß die Sekundärgaskappe (72) aus einem Metall gebildet wird und außerdem eine Einrichtung für das elektrische Isolieren der Sekundärgaskappe (72) aufweist, so daß sie elektrisch ungeerdet ist, um eine Ausbildung eines doppelten Lichtbogens zwischen ihr und dem Werkstück (36) zu vermeiden.

9. Plasmalichtbogenbrenner (10) nach Anspruch 8, dadurch gekennzeichnet, daß die elektrische Isoliereinrichtung ein Isolierelement (12a) umfaßt, das einen Abschnitt des Gehäuses (12) bildet, an dem die Sekundärgaskappe (72) auswechselbar befestigt ist.

10. Plasmalichtbogenbrenner (10) nach einem der Ansprüche 1 bis 9, dadurch gekennzeichnet, daß die Einrichtung für das Erzeugen einer sehr hohen Sekundärgasstrommenge eine Steuereinrichtung (44) für das Erzeugen einer Folge von Steuersignalen und einen Gaszuführkreislauf umfaßt, der auf die Steuereinrichtung anspricht, und der Sekundärgasströme mit hoher Menge mindestens während des Lochens und mit der Betriebsstrommenge erzeugt, wenn das Lochen abgeschlossen ist.

11. Plasmalichtbogenbrenner (10) nach Anspruch 10, dadurch gekennzeichnet, daß der Gaszuführkreislauf eine Einrichtung für das schnelle Zuführen der Gasströme zum Brenner (10) und eine Einrichtung für das schnelle Wegführen der Gasströme beim Abschluß des Lochens und danach beim Abschluß des Schneidens umfaßt.

12. Plasmalichtbogenbrenner (10) nach Anspruch 11, dadurch gekennzeichnet, daß die Einrichtung für

das schnelle Zuführen erste (76, 78) und zweite Leitungseinrichtungen (82) für das Führen des Plasma- und Sekundärgases zum Plasmagaseintritt (10a) und bzw. Sekundärgaseintritt (10b) des Brenners und elektrisch betätigte Ventileinrichtungen umfaßt, die parallel mit jeder ersten (76, 78) und zweiten Leitungseinrichtung (82) verbunden sind, wobei jede Ventileinrichtung, wenn sie geöffnet ist, einen plötzlich erhöhten Strom der Gase zum Brenner gestattet.

13. Plasmalichtbogenbrenner (10) nach Anspruch 12, dadurch gekennzeichnet, daß die Einrichtung für das schnelle Wegführen einen Satz elektrisch betätigte Magnetventile (SV8,9,10) in der ersten (76, 78) und zweiten Leitungseinrichtung (82) umfaßt, wobei ein Teil dieser den ausgewählten Gasstrom zum Brenner (10) plötzlich einstellt und ein zweiter Teil dieser sich öffnet, um den Brenner (10) und die Leitungseinrichtung in Abstimmung mit dem Schließen des ersten Teils zu entlüften.

14. Plasmalichtbogenbrenner (10) nach Anspruch 12, dadurch gekennzeichnet, daß der Sekundärgasstrom (46) mit hoher Strommenge ein Vorstrom in Verbindung mit der Funktionsweise nach der Betriebsart mit Zündlichtbogen ist, und daß die Einrichtung für das schnelle Wegführen mit einer geringen Verzögerung funktioniert, nachdem die Stromsteuereinrichtung den Vorstrom zugunsten eines Betriebsstromes beendet.

15. Verfahren zum Schützen der Düse (28) eines Plasmalichtbogenschneidbrenners (10) vor geschmolzenem Metall, das von einem metallischen Werkstück (36) während des Lochens des Werkstückes mittels eines übertragenen Plasmalichtbogens, der aus dem Brenner (10) emittiert wird, darauf gespritzt wird, wobei der Brenner (10) ein Gehäuse (12) mit einem Primärgaseintritt (10a) und einem Sekundärgaseintritt (10b), eine Elektrode (24) und eine Düse (28) in einer gegenseitig beabstandeten Beziehung in bezug auf die Elektrode (24) zum Bilden einer Plasmalichtbogenkammer (30) dazwischen, wo das Plasmagas ionisiert, aufweist, wobei es aufweist

das Lenken des Sekundärgases durch den Brenner (10) zu einer Austrittsöffnung (62), die unmittelbar angrenzend an den übertragenen Plasmalichtbogen (34) angeordnet ist, während er die Düse (28) verläßt;

das Erhöhen der Strommenge des Sekundärgases auf eine hohe Menge während des Lochens,

wodurch ein hoher Grad an Gleichmäßigkeit des Stromes des Sekundärgases erzeugt wird, während es aus der Austrittsöffnung (62) austritt,
dadurch gekennzeichnet, daß die hohe Menge ausreichend ist, um das gespritzte, geschmolzene Metall wegzublasen.

16. Verfahren für das Schützen der Düse nach Anspruch 20, dadurch gekennzeichnet, daß es außerdem das schnelle Zuführen des Sekundärstromes, wenn mit dem Lochen begonnen wird, und das schnelle Wegführen dieses aufweist, wenn das Lochen beendet wird.

17. Verfahren für das Schützen der Düse nach einem der Ansprüche 15 oder 16, dadurch gekennzeichnet, daß das Erzeugen eines sehr gleichmäßigen Stromes das Einführen eines Druckabfalls stromaufwärts von der Austrittsöffnung (62) und das Bilden eines Gasraumes zwischen der Stelle des Druckabfalls und der Austrittsöffnung (62) umfaßt.

18. Verfahren für das Schützen der Düse nach Anspruch 16, dadurch gekennzeichnet, daß das Zuführen die Verringerung des Strömungswiderstandes umfaßt, und daß das Wegführen das Entlüften des Sekundärstromes umfaßt.

19. Verfahren für das Betreiben eines Plasmalichtbogenschneidbrenners, das den Betrieb in einer Betriebsart mit Zündlichtbogen enthält und danach auf die Betriebsart mit übertragenem Lichtbogen für das Lochen eines Werkstückes aus Metall übergeht und anschließend das Werkstück durch translatorische Bewegung des Brenners schneidet, wobei der Brenner einen Plasmagasstrom und einen Sekundärgasstrom dort hindurch aufweist, wobei der Plasmastrom einen Zünd- und übertragenen Lichtbogen bildet und die Gasströme einen Vorstrom in Verbindung mit dem Lochen und einen Betriebsstrom in Verbindung mit dem Schneiden aufweisen, wobei es aufweist:

das Lenken des Sekundärstromes auf den Plasmastrahl,

und das Erhöhen der Sekundärstrommenge während des Lochens, verglichen mit einer Betriebsstrommenge für das Schneiden, wenn sich der Plasmastrahl in der Schneidbetriebsart befindet, dadurch gekennzeichnet, daß

die erhöhte Sekundärstrommenge ausreichend ist, um das gespritzte geschmolzene Metall wegzublasen, das vom Werkstück nach oben zum Brenner fliegt und daher die Ausbildung eines doppelten Lichtbogens oder ein

Durchtrennen hervorrufen könnte.

20. Verfahren nach Anspruch 19, dadurch gekennzeichnet, daß es außerdem aufweist:

das schnelle Zuführen des Sekundärgasstromes am Anfang als eine Stufenfunktion, um eine hohe Strommenge zu erzeugen

und das schnelle Wegführen des Sekundärgasstromes am Ende des Vorstromes des Sekundärgases.

21. Verfahren nach einem der Ansprüche 15 bis 20, dadurch gekennzeichnet, daß das Sekundärgas eine Mischung eines oxidierenden Gases und eines nichtoxidierenden Gases ist, die in einem Verhältnis im Bereich von etwa 2:3 bis etwa 9:1 oxidierendes Gas zu nichtoxidierendem Gas gemischt sind, gemessen als Strommengen der Gase.

22. Verfahren nach Anspruch 21, dadurch gekennzeichnet, daß das nichtoxidierende Gas aus der Gruppe ausgewählt wird, die aus Stickstoff und Argon besteht, und daß das oxidierende Gas aus der Gruppe ausgewählt wird, die aus Sauerstoff und Luft besteht.

23. Verfahren nach Anspruch 21 oder 22, dadurch gekennzeichnet, daß das Verhältnis annähernd 2:1 beträgt.

24. Verfahren nach einem der Ansprüche 15 bis 20, dadurch gekennzeichnet, daß das Sekundärgas eine Mischung eines nichtoxidierenden Gases und eines oxidierenden Gases ist, wobei die Mischung mindestens 40 % oxidierendes Gas aufweist, gemessen mittels der Strommenge.

25. Verfahren nach Anspruch 24, dadurch gekennzeichnet, daß das nichtoxidierende Gas aus der Gruppe ausgewählt wird, die aus Stickstoff und Argon besteht, und das oxidierende Gas aus der Gruppe ausgewählt wird, die aus Sauerstoff und Luft besteht.

Revendications

1. Torche de coupe à arc de plasma (10) utilisée pour percer et découper une pièce sous forme d'une tôle métallique (36), dans laquelle la torche a un corps (12), une électrode (24) et une buse (28) montée au niveau d'une première extrémité du corps en en étant espacée pour définir une chambre à plasma (30), un trajet de courant de gaz de plasma (48) dans ledit corps qui conduit un gaz de plasma depuis une arrivée de gaz de plasma (10a) à la chambre à plasma (30), un trajet de courant de gaz secondaire (50) dans ledit corps (12) depuis une arrivée de gaz secondaire (10b) jusqu'à un orifice de sortie (62) entourant ledit arc de plasma, la torche (12) fonctionnant en un mode d'arc pilote et en un mode d'arc transféré qui peut commencer en perçant la pièce,

des moyens pour procurer un débit volumétrique dudit gaz secondaire pendant ledit perçage qui est supérieur au débit volumétrique pendant la coupe dans le mode d'arc transféré, un capuchon de gaz secondaire (72) monté sur ledit corps en étant espace de ladite buse (28) pour définir entre eux une portion dudit trajet de courant du gaz secondaire qui contient ledit orifice de sortie (62) dudit courant de gaz secondaire ;
ledit orifice de sortie du courant de gaz secondaire (62) étant adjacent à l'orifice de sortie de buse (28a) de telle sorte que ledit courant de gaz secondaire est dirigé sur l'arc de plasma transféré lorsqu'il quitte ledit orifice de sortie de la buse sans être notablement ionisé,
ledit débit volumétrique du gaz secondaire à grande vitesse au niveau dudit orifice de sortie (62) étant (i) très uniforme, et (ii) positionné à proximité de l'arc de plasma transféré,
caractérisée en ce qu'un capuchon refroidi à l'eau (66) est monté sur ledit corps et enferme pratiquement la surface extérieure de la buse (28), lesdits moyens pour produire un débit volumétrique dudit gaz secondaire produisent un débit volumétrique pendant ledit perçage qui est très élevé par comparaison avec le débit volumétrique pendant la coupe dans le mode d'arc transféré de telle sorte que ledit courant de gaz secondaire à grande vitesse a une vitesse suffisante à l'extérieur de ladite torche entre ladite buse (28) et ladite pièce à usiner (36) pour éliminer par soufflage le métal en fusion qui rejaillit vers le haut de la pièce à usiner (36) jusqu'à la torche (12) pouvant ainsi procurer une double formation d'arc ou un évidement.

2. Torche à arc de plasma (10) selon la revendication 1, dans laquelle lesdits moyens pour produire un débit volumétrique de gaz secondaire très élevé comprennent une chambre préalable (58) dans ledit trajet du courant de gaz secondaire (50) immédiatement en amont dudit orifice de sortie (62) et au moins un moyen pour produire une chute de pression dans ledit trajet de courant secondaire (50) entre un point situé en amont de ladite pré-chambre (58) et la pré-chambre (58) elle-même.

3. Torche à arc de plasma (10) selon la revendication 1 ou la revendication 2, dans laquelle lesdits

moyens pour produire un débit volumétrique de gaz secondaire élevé et uniforme comprennent un anneau de tourbillonnement (60) disposé dans ledit trajet de courant du gaz secondaire (50) immédiatement en avant dudit orifice de sortie (62).

4. Torche à arc de plasma selon la revendication 2 ou la revendication 3, dans laquelle lesdits moyens pour produire une chute de pression comportent au moins un orifice de restriction du courant (56).

5. Torche à arc de plasma (10) selon la revendication 3 ou la revendication 4, dans laquelle ladite torche (10) est une torche à haute définition et dans laquelle lesdits moyens pour produire un débit volumétrique de gaz secondaire élevé (50) comprennent :

(i) un capuchon refroidi à l'eau (66) monté sur ledit corps (12) et entourant pratiquement la surface extérieure de la buse (28) en en étant espacé pour définir une chambre à eau (70) pour refroidir la buse (28), et
(ii) un capuchon de gaz secondaire (72) monté sur ledit corps (12) en étant espacé dudit capuchon refroidi à l'eau (66) pour définir entre eux ladite pré-chambre (58), ledit anneau de tourbillonnement (60) étant monté entre ledit capuchon refroidi à l'eau (66) et ledit capuchon de gaz secondaire (72) adjacent à leurs extrémités proches de la buse (28).

6. Torche à arc de plasma (10) selon la revendication 5, dans laquelle ledit orifice de restriction de courant (56) est formé dans ledit capuchon refroidi à l'eau (66) près de l'extrémité amont de ladite pré-chambre (58).

7. Torche à arc de plasma (10) selon la revendication 5, dans laquelle ledit capuchon de gaz secondaire (72) est formé d'une première portion (72a) qui est fixée sur le corps de la torche (12) et qui se projette vers ladite buse (28), et d'une deuxième portion (72d) tenue de façon remplaçable entre ladite première portion (72a) et ledit anneau de tourbillonnement (60), ladite deuxième portion (72d) étant fixée de façon étanche à ladite première portion (72a) en une relation d'étanchéité au gaz et s'étendant sensiblement parallèle à la pièce à usiner (36), sauf en ce qui concerne l'orifice de sortie central (72i) pour l'arc de plasma transféré.

8. Torche à arc de plasma (10) selon la revendication 7, dans laquelle ledit capuchon de gaz secondaire (72) est formé d'un métal et comprend en outre des moyens pour isoler électriquement ledit capuchon de gaz secondaire (72) de telle sorte qu'il est électriquement isolé de la terre pour éviter une double formation d'arc entre lui et la pièce à usiner.

9. Torche à arc de plasma (10) selon la revendication 8, dans laquelle lesdits moyens électriquement isolants comprennent un élément isolant (12a) formant une portion dudit corps (12) sur laquelle ledit capuchon de gaz secondaire (72) est fixé de façon remplaçable.

10. Torche à arc de plasma (10) selon l'une des revendications 1 à 9, dans laquelle lesdits moyens pour produire un débit volumétrique de gaz secondaire très élevé comprennent des moyens de commande (44) pour générer une séquence de signaux de commande et un circuit de délivrance des gaz sensible auxdits moyens de commande, qui produisent des courants de gaz secondaire audit débit élevé au moins pendant le perçage et audit débit volumétrique opérationnel lorsque le perçage est termine.

11. Torche à arc de plasma (10) selon la revendication 10, dans laquelle ledit circuit de délivrance des gaz comprend des moyens pour charger rapidement lesdits courants de gaz à la torche (10) et des moyens pour décharger rapidement les courants de gaz à la fin dudit perçage et ensuite à la fin de ladite coupe.

12. Torche à arc de plasma (10) selon la revendication 11, dans laquelle lesdits moyens de charge rapide comprennent des premiers moyens (76, 78) et des deuxièmes moyens de conduit (82) pour conduire lesdits gaz de plasma et secondaire à ladite arrivée de gaz de plasma (10a) et à ladite arrivée de gaz secondaire (10b) de ladite torche respectivement, et des moyens de vanne à commande électrique montés en parallèle avec chacun desdits premiers (76, 78) et deuxième (82) moyens de conduit, chacun desdits moyens de vanne, lorsqu'ils sont ouverts, permettant une soudaine augmentation du courant desdits gaz à ladite torche.

13. Torche à arc de plasma (10) selon la revendication 12, dans laquelle lesdits moyens de décharge rapide comprennent un jeu d'électrovannes à commande électrique (SV8, 9, 10) dans lesdits premiers (76, 78) et deuxièmes (82) moyens de conduit, dont une portion coupe brutalement un courant de gaz sélectionné arrivant à ladite torche (10), et dont une deuxième portion s ouvre pour mettre à l'air libre la torche (10) et lesdits moyens de conduit en coordination avec la fermeture de la première portion.

14. Torche à arc de plasma (10) selon la revendication 12, dans laquelle ledit courant de gaz secondaire à débit volumétrique élevé (46) est un courant préalable en conjonction avec un fonctionnement dans le

mode d'arc pilote et dans laquelle lesdits moyens de décharge rapide entrent en oeuvre avec un léger retard après que les moyens de commande de courant ont terminé ledit courant préalable en faveur d'un courant opérationnel.

15. Procédé pour protéger la buse (28) d'une torche de coupe à arc de plasma (10) contre le métal en fusion projeté sur elle depuis une pièce métallique à usiner (36) pendant le perçage de la pièce par un arc de plasma transféré émis de la torche (10), la torche (10) comprenant un corps (12) avec une arrivée de gaz primaire (10a) et une arrivée de gaz secondaire (10b), une électrode (24) et une buse (28) espacée de l'électrode (24) pour former entre elles une chambre à arc de plasma (30) où le gaz de plasma est ionisé, comprenant les étapes suivantes :

- diriger le gaz secondaire à travers la torche (10) jusqu'à un orifice de sortie (62) placé immédiatement adjacent à l'arc de plasma transféré (34) lorsqu'il quitte la buse (28),
- augmenter le débit volumétrique dudit gaz secondaire jusqu'à un débit élevé pendant le perçage,
- d'où il résulte qu'un degré élevé d'uniformité de courant dudit gaz secondaire est créé lorsqu'il sort dudit orifice de sortie (62),
  caractérisé en ce que ce débit élevé est suffisant pour éliminer par soufflage le métal en fusion projeté.

16. Procédé de protection d'une buse selon la revendication 20, comprenant en outre l'étape dans laquelle on charge rapidement ledit courant secondaire lorsque le perçage commence et on le décharge rapidement lorsque le perçage est terminé.

17. Procédé de protection d'une buse selon l'une des revendications 15 ou 16, dans lequel ladite création d'un courant extrêmement uniforme comprend l'étape dans laquelle on introduit une chute de pression en amont dudit orifice de sortie (62) et on crée une réserve de gaz entre le point de ladite chute de pression et ledit orifice de sortie (62).

18. Procédé de protection d'une buse selon la revendication 16, dans lequel ladite charge comprend l'étape dans laquelle on réduit la résistance audit courant et ladite décharge comprend l'étape dans laquelle on met ledit courant secondaire à l'air libre.

19. Procedé de mise en oeuvre d'une torche de coupe à arc de plasma, comprenant un fonctionnement en un mode d'arc pilote et le transfert ensuite à un mode d'arc transféré pour percer une pièce métallique et pour couper ensuite la pièce en déplaçant la torche en translation, où la torche a un courant de gaz de plasma et un courant de gaz secondaire la traversant, le courant de plasma formant l'arc pilote et l'arc transféré et lesdits courants de gaz ayant un courant préalable associé audit perçage et un courant opérationnel associé à ladite coupe, comprenant les étapes suivantes :

- diriger ledit courant secondaire sur ledit jet de plasma, et
- augmenter ledit débit volumétrique du gaz secondaire pendant le perçage par comparaison au débit volumétrique opérationnel pour la coupe lorsque ledit jet de plasma est dans le mode de coupe,
  caractérisé en ce que ledit débit volumétrique secondaire augmenté est suffisant pour éliminer par soufflage le métal en fusion pulvérisé qui est projeté vers le haut depuis la pièce vers la torche et qui peut produire une double formation d'arc ou un évidement.

20. Procédé selon la revendication 19, comprenant en outre les étapes suivantes :

- charger rapidement ledit courant de gaz secondaire au début pour produire ledit débit volumétrique élevé en tant que fonction à échelons, et
- décharger rapidement ledit courant de gaz secondaire à la fin dudit courant préalable dudit gaz secondaire.

21. Procédé selon l'une des revendications 15 à 20, dans lequel ledit gaz secondaire est un mélange d'un gaz oxydant et d'un gaz non oxydant mélangés en un rapport dans la plage d'environ 2:3 à environ 9:1 de gaz oxydant par rapport au gaz non oxydant, mesuré en tant que débits volumétriques desdits gaz.

22. Procédé selon la revendication 21, dans lequel ledit gaz non oxydant est choisi dans le groupe comprenant l'azote et l'argon et ledit gaz oxydant est choisi dans le groupe comprenant l'oxygène et l'air.

23. Procédé selon la revendication 21 ou la revendication 22, dans lequel ledit rapport est environ 2:1.

24. Procédé selon l'une des revendications 15 à 20, dans lequel ledit gaz secondaire est un mélange d'un gaz non oxydant et d'un gaz oxydant, dans lequel le mélange comprend au moins 40 % de gaz oxydant, comme mesuré par les débits volumétriques.

25. Procédé selon la revendication 24, dans lequel ledit gaz non oxydant est choisi dans le groupe compre-

nant l'azote et l'argon et ledit gaz oxydant est choisi dans le groupe comprenant l'oxygène et l'air.

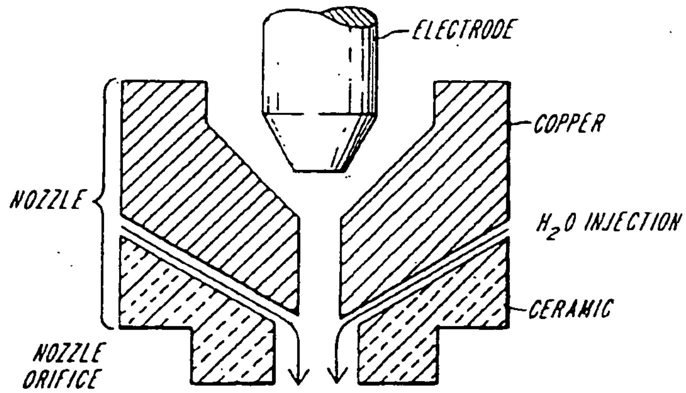


FIG. 1A
(PRIOR ART)

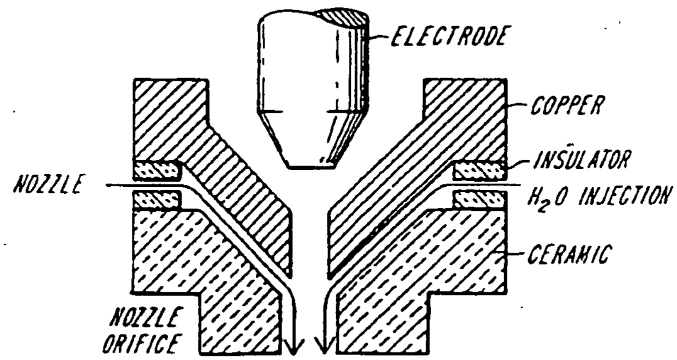


FIG. 1B
(PRIOR ART)

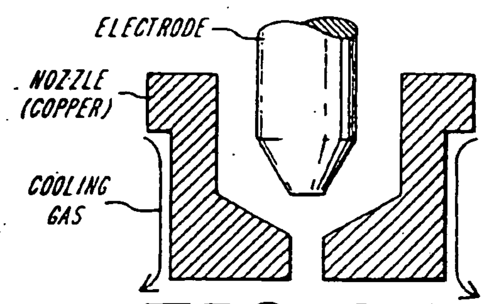


FIG. 2A
(PRIOR ART)

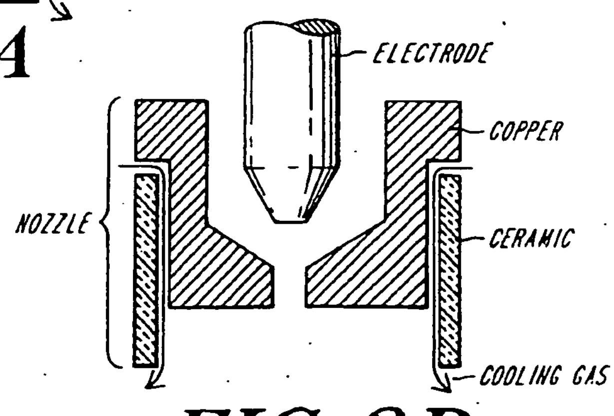
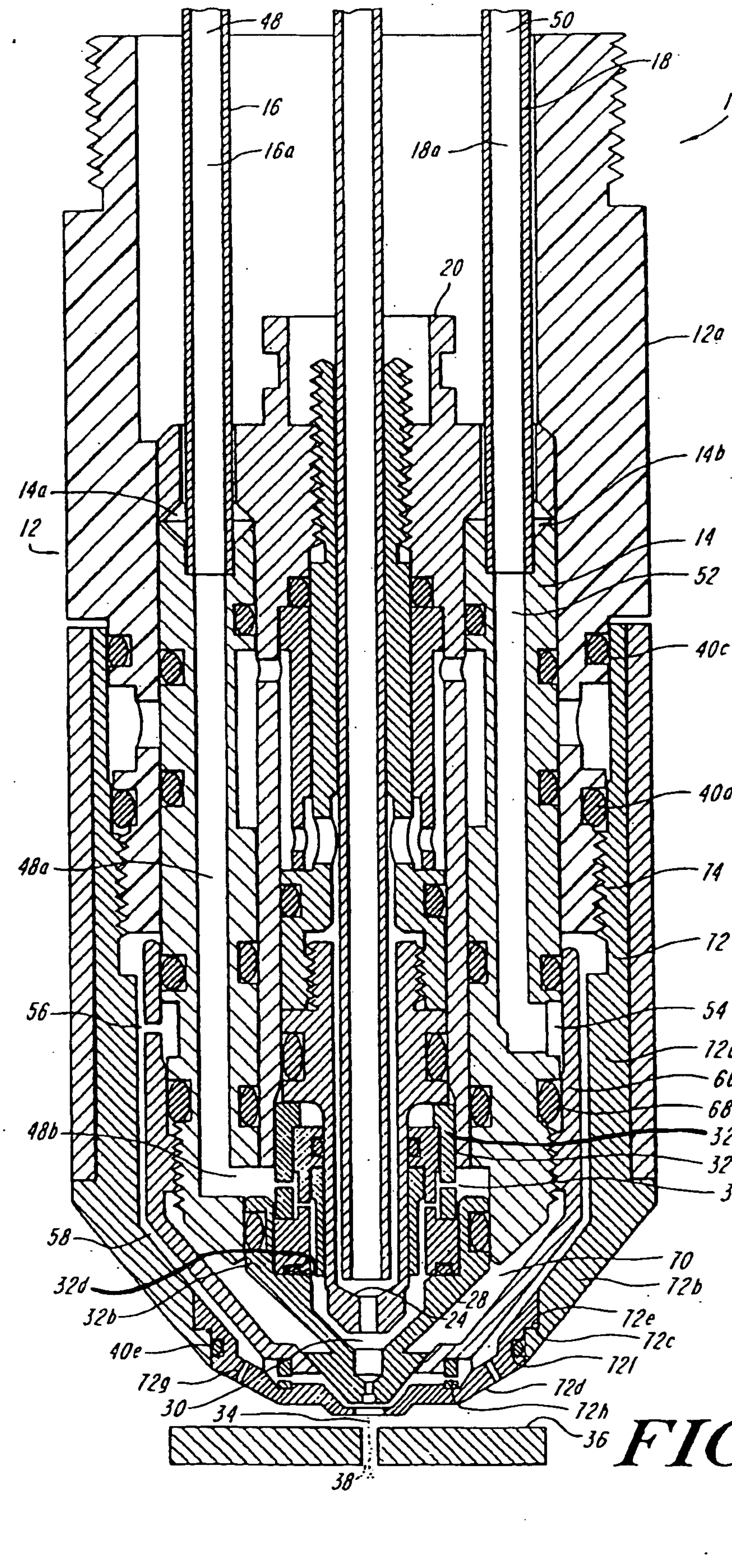


FIG. 2B
(PRIOR ART)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16a
18a
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14b
14a
12
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52
40c
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56
54
72a
66
68
48b
32a
32
32c
58
70
32d
72b
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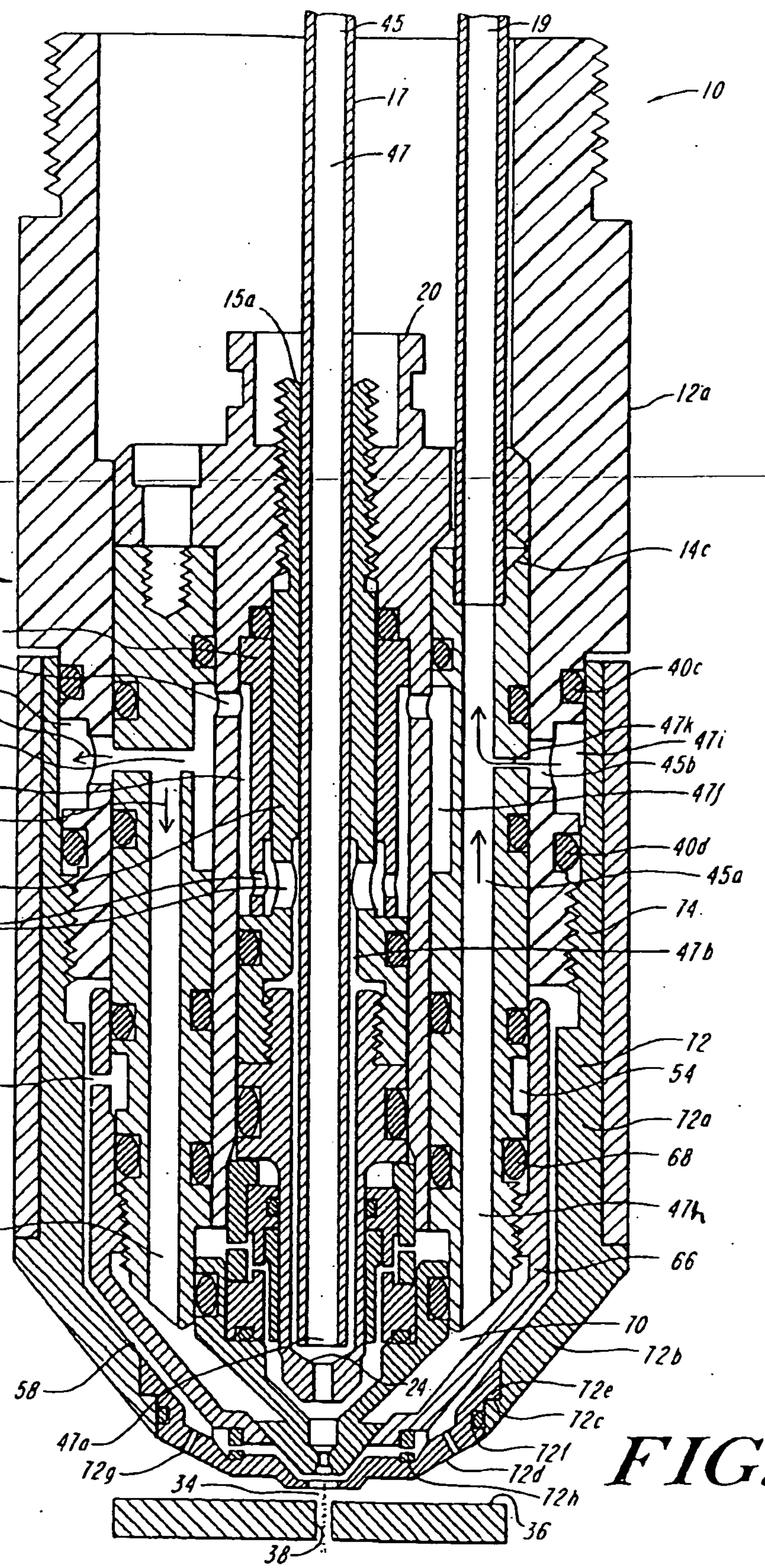
32b
24
72e
72c
40e
121
72g
72d
30
72h
34
36
38

FIG. 3A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45b
47j
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45a
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47c
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47h
47h
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72d
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72h
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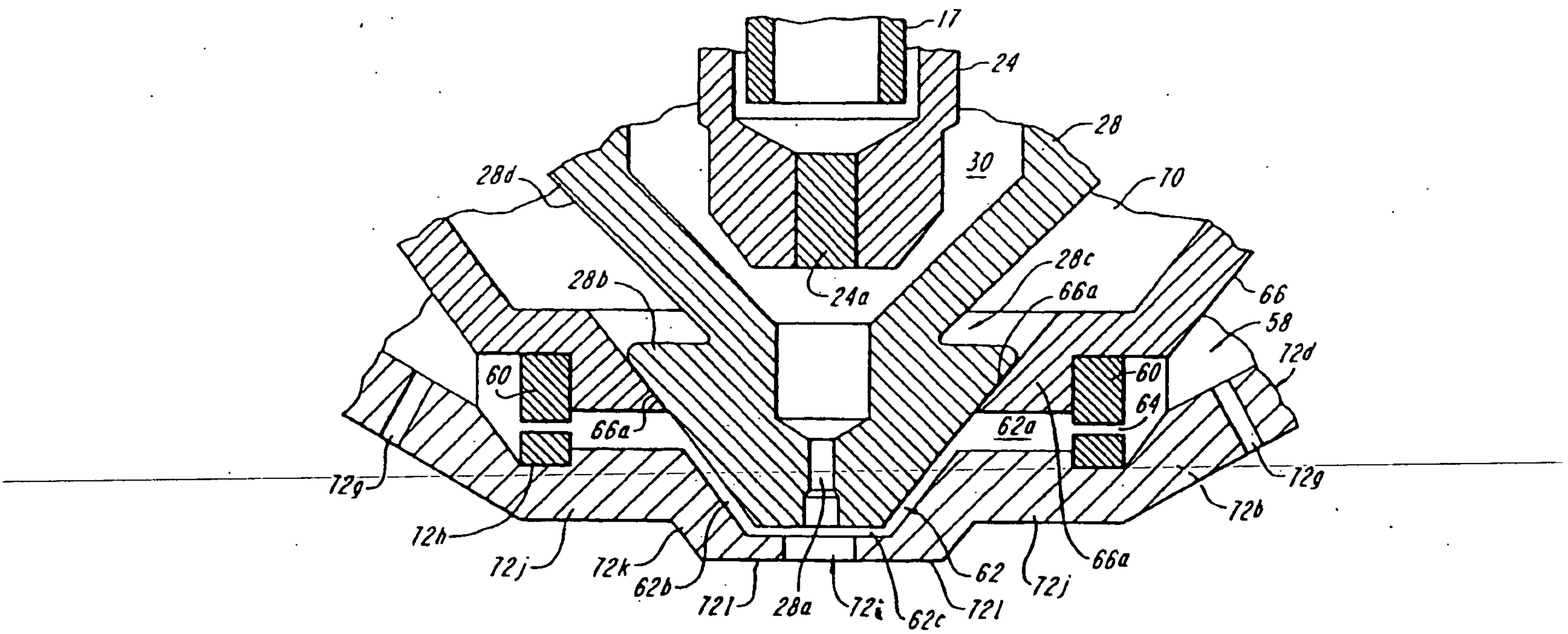
38

FIG. 3B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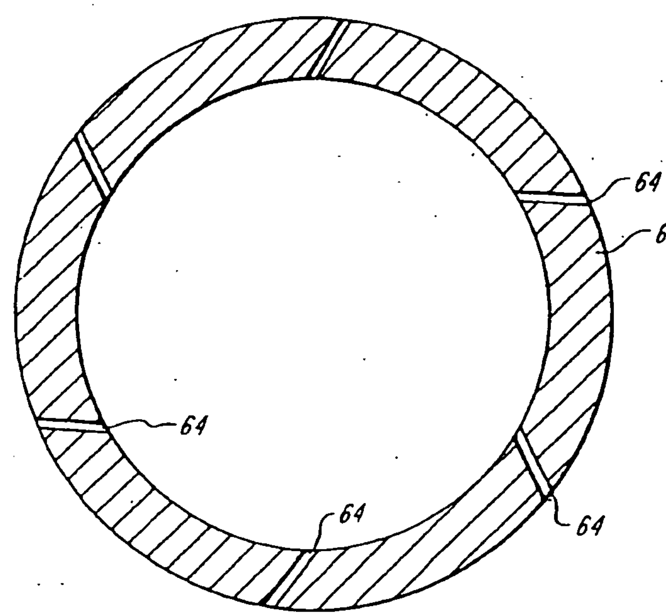
72g
72g
72b
72h
66a
72j
72k
62
72j
62b
72l
28a
72i
62c
72l

FIG. 3C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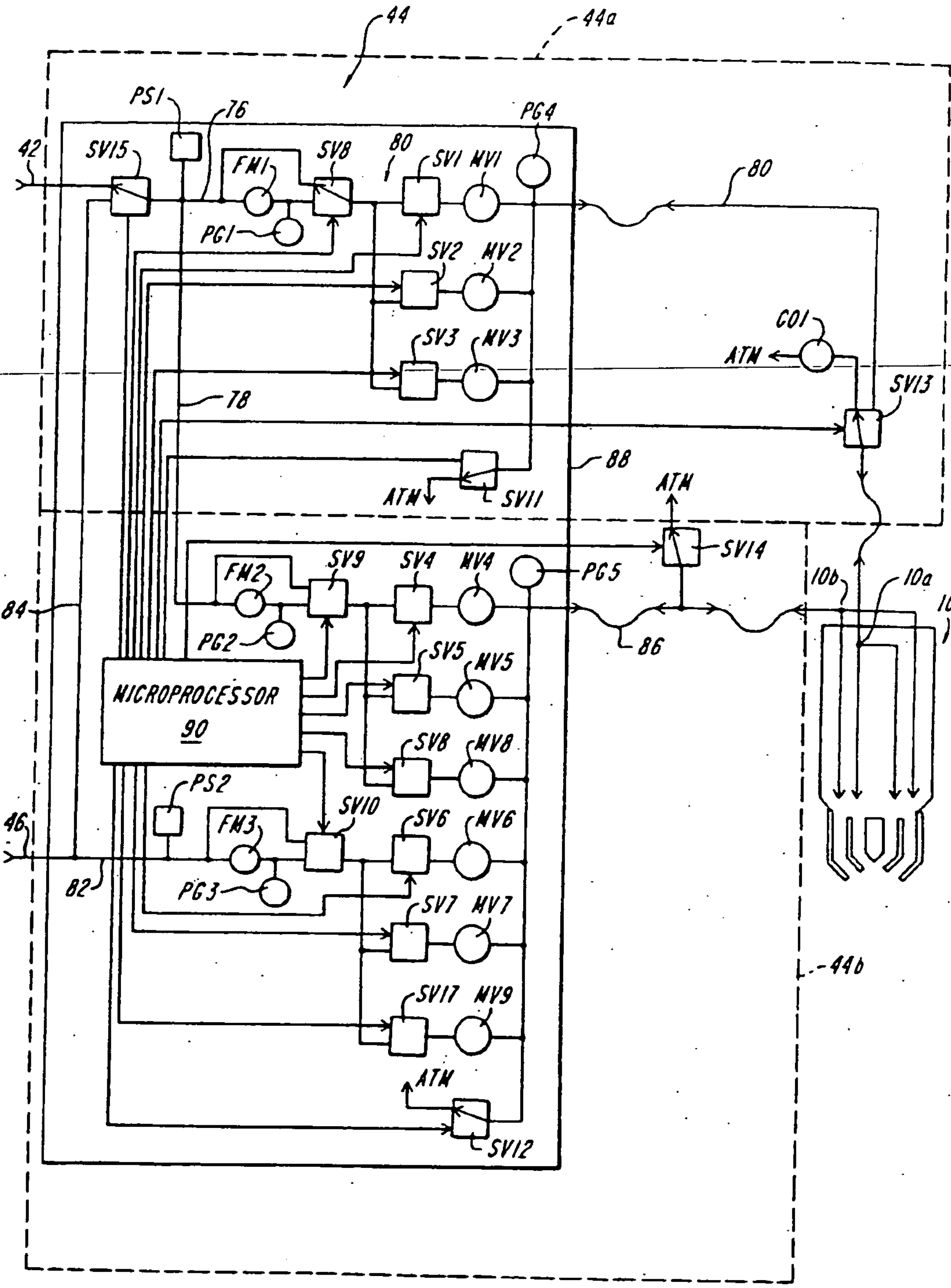
64

FIG. 3D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ATM
SV3
MV3
SV13
78
88
ATM
SV11
ATM
SV14
FM2
SV9
SV4
MV4
PG5
10b
10a
10
84
PG2
86
SV5
MV5
MICROPROCESSOR
90
SV8
MV8
PS2
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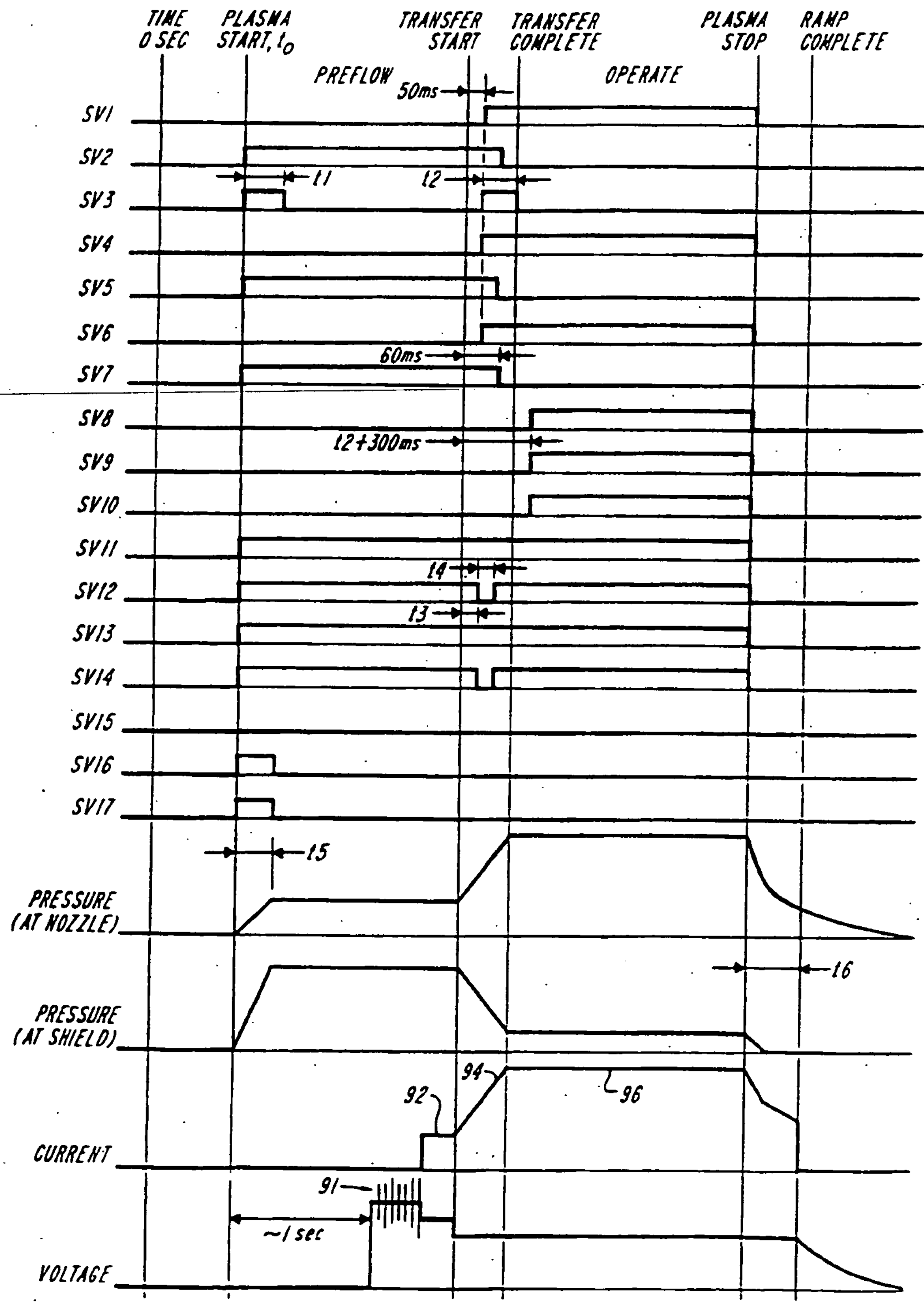
FM3
SV10
SV6
MV6
82
PG3
SV7
MV7
44b
SV17
MV9
ATM
SV12

FIG. 4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TRANSFER COMPLETE
PLASMA STOP
RAMP COMPLETE
PREFLOW
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t2
60ms
t2+300ms
t4
t3
t5
t6
SV1
SV2
SV3
SV4
SV5
SV6
SV7
SV8
SV9
SV10
SV11
SV12
SV13
SV14
SV15
SV16
SV17
PRESSURE (AT NOZZLE)
PRESSURE (AT SHIELD)
CURRENT
VOLTAGE
91
92
94
96
~1 sec

FIG. 5